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Ensuring performance by geometric quality control and specifications for parabolic trough solar fields

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Abstract

Solar field thermal output depends on the optical, geometrical and thermal parameters of the installed solar collectors. In addition to appropriate collector design and quality of the components, proper assembly and installation processes are most relevant for high performance. Target values for the intercept factor are in the range of 96-99% for typical operating conditions. These values can only be reached if appropriate quality specifications are fulfilled. Specification values are suggested and their implications on intercept factors are discussed based on the well-proven statistical calculation model from Bendt and Rabl. A variety of measurement techniques which can be applied for measurement and control of the geometry parameters are discussed. The application of geometric quality control measurement techniques for prototype collector development as well as for series production of large fields has already contributed to relevant performance increase of parabolic trough collector fields and is constantly required to maintain high output quality of solar field design, production, and assembly.

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Keywords: Quality Control; Parabolic Trough; Specifications; Solar Field Assembly; Intercept Factor, Optimization, Photogrammetry, Deflectometry

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1. Introduction

The performance of parabolic trough collectors depends on their optical, thermal, and geometric properties under operating conditions. Many parameters are given by the selection of the collector geometry, collector stiffness and their components like receivers, mirror panels, drive and control characteristics. The component properties have to be defined in the purchase contracts and spot checked during the delivery at the project site. They influence the thermal collector efficiency through the intercept factor as well as through their optical and thermal properties, and are assessed with test methods developed in testing laboratories, such as the QUARZ laboratory at DLR in Germany [1-3] and NREL in the United States [4]. In the last decade, a variety of theoretical and practical characterization methods have been designed, developed and qualified to optimize parabolic trough prototypes and large solar fields. Besides rigorous deterministic ray-tracing and flux measurement studies [5,6] the statistical ray-tracing method from Bendt and Rabl [7,8] has been revived and successfully used for quality assessments of solar fields. One of the first widely used characterization methods for quantitative measurements was close range digital photogrammetry [9,10]. It permits the characterization of collector shape deviations from the nominal values and deformations under gravitational loads and torsion effects. The Camera Target Method (CTM) [5,11] was developed for spot checks of the intercept value of tracking parabolic trough collectors. It applies flux measurement know-how of central receiver systems to parabolic troughs. The deflectometry based absorber reflection method TARMES [12,13] was established for measuring mirror shape deviations of installed parabolic trough modules. A quadcopter based system has been developed with automated image acquisition to apply deflectometry, photogrammetry and thermography for checking of large areas or an entire solar field [14]. With implementation of proper quality assurance methods during the module assembly, e.g. with photogrammetry and deflectometry [15-18] and appropriate quality assurance during the solar field installation, the solar field should operate at optimum efficiency right at startup. However, it has been observed in measurement campaigns that existing solar fields can have significant optimization potentials.

2. Quality specifications and their relevance for the intercept factor

2.1. Statistical ray-tracing approach

Although deterministic ray-tracing is widely available to scientifically study all types of geometrical errors of concentrators [5,19], this is a rather complex and time consuming measure for assessing complete solar fields consisting of thousands of parabolic trough modules. It is straight forward to reduce the computation effort by using the statistical ray-tracing method of Bendt and Rabl [7,8], which does not require high-resolution measurements and delivers results, accurate enough to evaluate the state of the installed collectors. Thus the influence of the geometric concentrator quality on the intercept factor of collectors or whole solar fields is estimated. The approach uses normal distribution functions of angular deviations from the perfect optics (measured in mrad) to describe all kinds of geometric imperfections. Each component i contributing to the intercept factor quality is described by the standard deviation σ_i ("beam spread") of its distribution function. As usual for studies with a large number of independent, stochastically varying inputs, the individual parameter is replaced by the statistical model of a Gaussian distribution characterized by its standard deviation. The beam spread of the sunrays, when interacting with the imperfect concentrator, is represented by twice the standard deviation of the local mirror surface slope deviation values. The same method is applied to further geometric qualities, such as the alignment of mirror panels on the collector structure, the absorber tube alignment in the modules, and the tracking alignment. Some of these effects can again be subdivided if they are independent, for example angular alignment between collector modules, collector torsion due to dead load, wind load, and tracking system. Bendt and Rabl also suggest a Gaussian approximation for the sunbeam spread due to the size of the solar disc and circumsolar radiation. Using this model, the effect of geometry imperfections can be represented by summing the squares of the individual standard deviations. Parameters for the mirror slope are weighted by 2 to account for the double effect of mirror slope deviation on total beam spread.

$$\sigma_{total}^2 = \sum_i (a_i \cdot \sigma_i)^2 + \sigma_{sun}^2 \tag{1}$$

As result of this concept, the intercept factor of the trough collector depends on trough rim angle, concentration factor, incident angle, and on the total beam spread σ_{total} (Figure 1, left). Bendt and Rabl describe the effect of the angle of incidence on the ray-tracing with the apparent widening of the sun disc when incidence angles increase which leads to an increase in travel path of the reflected ray from the mirror to the absorber. Figure 1 (right) shows the resulting effect of intercept factor reduction that gets relevant during the winter period when the incident angle is larger than 30° at noon for the north-south oriented trough collector.

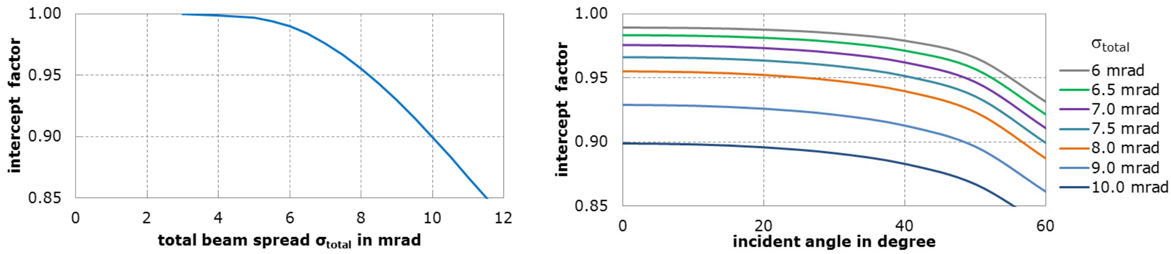


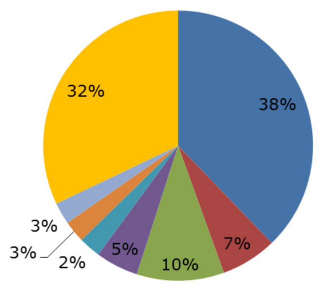
Figure 1. Left: Statistical ray-tracing result for intercept factor plot against total beam spread. Right: Effect of total beam spread and incident angle on intercept factor. Both graphs are for EuroTrough collector geometry.

The statistical approach has some limitations with non-Gaussian distribution in case such effect dominates the total beam spread. This happens if the sun shape governs the square sum of deviations in case of very high overall geometric accuracy. Asymmetric effects can be calculated separately if necessary [20]. Comparisons show that for most cases the used approach is appropriate for more general effects, unless specific details have to be considered.

2.2. Influence of collector quality on intercept factor

Under good overall operating conditions, a total quality σ_{total} of 6-6.5 mrad can be reached for a well-designed and well-built trough collector. This has been demonstrated by applying quality control measures in series production, including deflectometric measurements for mirrors and modules and 3D point measurements for metal framework structures. It is essential to achieve a well-balanced quality over all involved components and assembly steps. The following table and chart show an example of achievable geometric quality, expressed according to the statistical ray-tracing model in standard deviation parameters σ_i. In this set of examples the total quality is 6.2 mrad, and an intercept factor of 98.7 % is expected according to Table 1. This example shows the remaining optimization potential in concentrator mirror shape. Closer analysis reveals the sensitivity of the system for absorber tube alignment and tracking accuracy [19]. The analysis can also be extended to longer time periods such as a year including incident angle variations. To ease the evaluation, systematic effects are not considered in Table 1.

Table 1: Example of beam spread and total geometric quality for a EuroTrough collector geometry. The diagram illustrates the percentage share of the various error causes on the total beam spread.



	σ in mrad	weighting factor a_i	$(a_i\sigma_i)^2$ in mrad²
Mirror Shape	1.9	2	14.4
Mirror Support Position	0.8	2	2.6
Mirror Support Angle	1.0	2	4.0
Absorber Tube Position	1.4	1	2.0
Module Alignment	1.0	1	1.0
Collector Torsion (no wind)	1.0	1	1.0
Tracking Accuracy	1.0	1	1.0
Linear Sun Shape	3.5	1	12.3
Total	**6.2**	←	**38.3**
Intercept Factor	**98.7 %**		

An even higher impact on intercept factor than from such stochastic deviations is caused by systematic and asymmetric effects. Examples of asymmetric shape deviations are caused by weak receiver supports, deviations of the center of gravity from the rotation axis and tracking sensor offset. Symmetric systematic effects are too open or too closed mirror panels and/or concentrator shapes. The ray-tracing model has been adapted to accommodate for such effects. Figure 2 shows the intercept factor result for systematic tracking deviations with an aligned absorber tube (green curve) and with systematic absorber tube displacement; i.e. tube misalignment (red curve). The model also predicts the option to compensate systematic alignment deviations with an offset in the tracking angle.

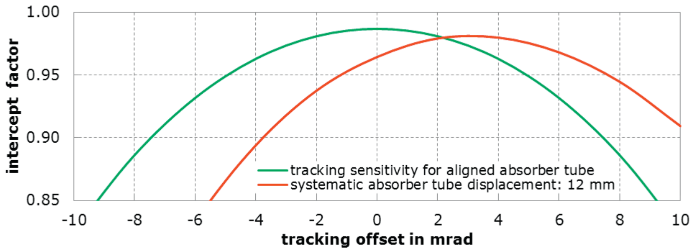


Figure 2. Intercept factor for aligned absorber tube and systematic absorber displacements as function of the tracking offset angle.

2.3. Specification values

Measurements of collectors in solar fields of commercial power plants have revealed numbers for quality parameters that can be achieved in mass production. On the basis of this experience and the ray-tracing considerations, Table 2 suggests desired maximum RMS (Root Mean Square) deviations for geometric quality parameters for collectors of EuroTrough dimensions. It also defines these values and suggests proven measurement methods to assess them. Obeying these values leads to a parabolic trough solar field with high overall concentrating performance.

Table 2. Quality specifications of EuroTrough sized parabolic trough collectors for different criteria.

quality	quality parameter and suggested specification	test method for production control, and frequency	test method for prototype or independent spot checks
structure: mirror support position (assembly)	mirror tilt alignment < 0.8 mrad RMS	automatic photogrammetry, surveying, laser tracker 20-100%	manual photogrammetry (also deformation studies), laser tracker
structure: mirror support bracket slope effects (assembly)	effect of mirror support bracket slope deviation on mirror geometry < 1 mrad RMS	automatic photogrammetry with orientation measurement adapters 20-100%	manual photogrammetry, inclinometers
mirror panel shape (fabrication)	slope deviation < 1.9 mrad RMS	automatic deflectometry 20-100%	manual deflectometry
absorber tube alignment (assembly)	lateral deviation of absorber tube position < 3 mm RMS	automatic photogrammetry, tachymetry 20-100%	hook rod
module alignment (field installation)	deviation of module alignment to drive < 1 mrad RMS	tachymetry, inclinometer, water level 100%	(robotic) tachymetry, water levels
collector torsion (field installation)	torsion between drive and all modules < 1 mrad RMS	inclinometers spot checks	inclinometers
tracking accuracy (field operation)	deviation of optical axis < 1 mrad RMS	inclinometers 100%	inclinometers, Camera Target Method

Statistical ray-tracing is applied on the specification values for a sun incidence angle of 30°. In Figure 3 the slope deviation of the mirror panels is kept constant to 1.9 mrad (corresponds to an FDx value of 8 mm), all other parameters are changed to a multiple of the suggested quality specifications. Figure 3 shows the significance of the quality specifications on the intercept factor of collectors that fulfill the specifications in comparison to reduced quality, in the examples with twice and triple standard deviation of the quality parameters.

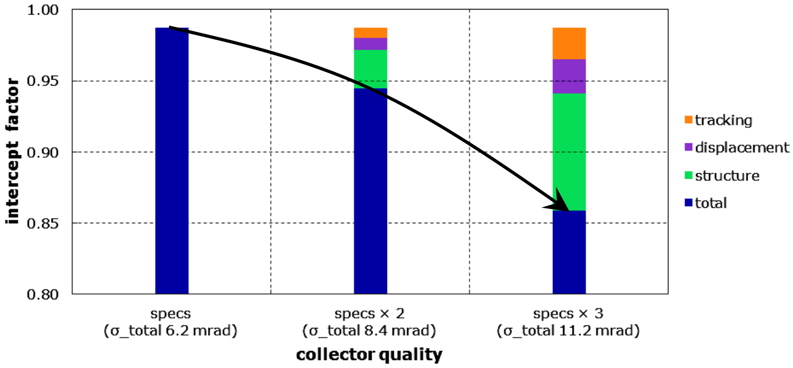


Figure 3. Intercept factor values for different collector qualities. The orange, purple and green bars show the effects of the individual error type on the intercept factor. The blue bar gives the overall intercept factor for doubling or tripling the geometric deviations.

As individual errors add quadratically to the total beam spread, a single high error can lead to a significant beam spread and hence reduction of the intercept factor. It is therefore essential to achieve a well-balanced quality over all involved components and assembly steps. For the given parameters, test methods have been developed and are applied systematically in qualification and testing of parabolic trough collectors, but also on any other concentrating solar system. The application range includes prototype tests, pilot scale and demonstration loop evaluation, milestone spot checks in construction, series production quality control, and final acceptance.

3. Quality control in mass production

3.1. Shape of trough structure without mirror panels

For the assembled trough structures, information of various geometrical parameters is desired: location of rotation axis as reference, location of mirror attachment points, slope of mirror support brackets, location of receiver supports, and length of trough module. From these values the deviations from the nominal data are calculated and compared to the specified tolerances. In various field measurements it was discovered that the slope deviations of mirror brackets and of the mirror panel mounting pads may cause significant intercept reductions. Hence the slope of the mirror brackets should be controlled. However the effective influence of these deviations on the concentrator slope has to be derived on the mirrored concentrator. The geometric measurement is performed in the production line to detect and eliminate errors in the assembly process. Sample tests from some modules per shift, and up to complete 100% tests are common. Precise, quick and widely automatic measurement without influence from the operator on the results is anticipated and the results should not depend on environmental conditions. Four types of instruments are commonly used for the quality assessment of trough metal structures: tachymeters, laser trackers, the Laser Radar and the QFoto photogrammetry system. Tachymeter and laser trackers are used with prism spheres which are placed manually on the measurement points one after another. This is time consuming and may influence the measurement results. The measurement accuracy of tachymeters is limited to around 1 mm. The Laser Radar measures on steel balls, placed at the measurement spots. It is also able to measure directly on the surfaces of the metal structure; however measurement time might increase for achieving sufficient accuracy. QFoto uses flat retro-reflective targets which are placed on the structure before measurement. By using special adapters it delivers mirror brackets locations and slopes simultaneously within a few minutes after measurement start. The Laser radar, laser tracker and tachymeter based system have the advantage that they can be more easily installed than the larger photogrammetry systems. A photogrammetry system has the advantage of low measurement uncertainty (< 0.5 mm) in a reasonable measurement time without user interference during the measurement [15,16].

3.2. Shape of complete trough concentrator

Using a deflectometric method, the shape of mirrored concentrators can be assessed in high resolution. In the last years, deflectometry has been applied for the measurement of shape of single mirror panels [17]. Current optimizations extend the application to wider mirror geometry ranges including complete parabolic trough modules [18]. Mirror panel slope deviation or misalignment deflect the sun rays twofold due to the law of directed reflection. Hence the most important value regarding efficiency is the RMS value of all local focus deviations of the complete concentrator (FDx), usually for 0° incident angle. Local focus deviation (fdx) is defined as the minimum distance of the reflected ray from the focal line [21]. Table 1 suggests a total slope deviation smaller than 2.3 mrad (square sum of 0.8, 1.0 and 1.9 mrad) for a mirrored module to achieve a high intercept factor. This corresponds to an FDx of approximately 10 mm or, more generally, 1/7 of the receiver tube diameter. The following specifications are recommended for a measurement system: uncertainty for complete concentrator shape below 0.2 mrad (RMS) (obeying the golden rule of measurement to measure with an uncertainty below 1/5 to 1/10 of the desired tolerance value), quick and widely automatic measurement without influence of the operator on the results.

3.3. Balancing of trough modules

The center of gravity of trough modules must be in the rotation axis in order to avoid torsion due to imbalance of the collectors during tracking. Commercial steel profiles and their galvanization layers exhibit variations from specified thickness and therefore weight. Depending on the collector design and its stiffness, balancing of the collector modules is common practice. Commercial torque sensors or hydraulic systems with pressure gauges are used for controlling the effect of imbalance on the collector tracking. The required precision of the measurement apparatus depends on the stiffness of the chosen collector type which influences torsional effects [22].

4. Quality control for prototypes and in solar field installation

4.1. 3D geometry of trough module

Manual photogrammetry [9,10] is applied to evaluate the collector module geometry in the field. This measurement can be performed with the appropriate reflective targets and adapters on modules with and without installed mirror panels. The measurement has the advantage that the geometry can be assessed and compared in different tracking angles. Besides 3D results in zenith, dead load and torsion deformation values are determined. Figure 4 shows the results of a photogrammetry measurement and post-processing.

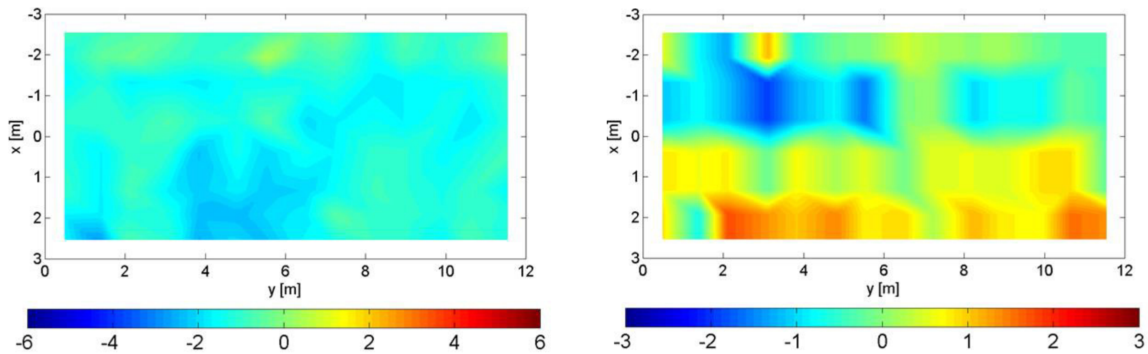


Figure 4. Typical photogrammetry result for one parabolic trough module in zenith angle. Left: graph of height deviations from nominal with 1.4 mm of RMS. Right: graph of mirror tilt deviations from nominal with 0.9 mrad (RMS). Color bars in mm and mrad, respectively

The versatile and mobile measurement equipment can be easily transported to any solar field or test location. Current evaluation tools permit the analysis of all types of trough geometries. Most relevant data is extracted out of large point clouds with the post-processing algorithms. The following data is obtained: Structure or mirror panel 3D shape geometry and deformation, rotation axis position, receiver supports position and deformation. Relevant deviations and deformations can be analysed and measures for improvements undertaken. The tests and evaluations are typically applied for prototype collectors and pilot test loop installations to verify the concentrator design.

4.2. Shape of complete concentrator

While photogrammetry is well adapted to the measurement in low resolution, high accuracy deflectometry methods are used for high resolution measurements of the reflector surface slope deviations. Here, a distant camera takes the image of the receiver tube reflected in the concentrator mirror. By rotating the concentrator in small steps around its axis or by moving the camera, the receiver image reflected into the mirrors changes and the mirror slope deviations can be derived. Examples of these types of measurement systems are TARMES (DLR, CSP Services) [12,13], VShot (NREL) [23] and VIS (Marposs) [24]. For TARMES the output of the measurement are slope and focus deviation values with spatial resolution and as summary parameters. Deterministic ray-tracing post-processing delivers space-resolved intercept factor values. TARMES measurements are performed in different collector angles. To increase the measurement volume, speed and convenience, the camera can be combined with a quadcopter system to enable airborne image acquisition [14,25]. The technique has been successfully developed and validated [14] and will permit the measurement of larger collector surfaces. Additional results are the absorber tube position and, using an infrared camera, quantitative information about receiver glass tube temperature. Figure 5 displays the slope deviation map and the intercept factor map of a EuroTrough-sized collector module inspected by TARMES.

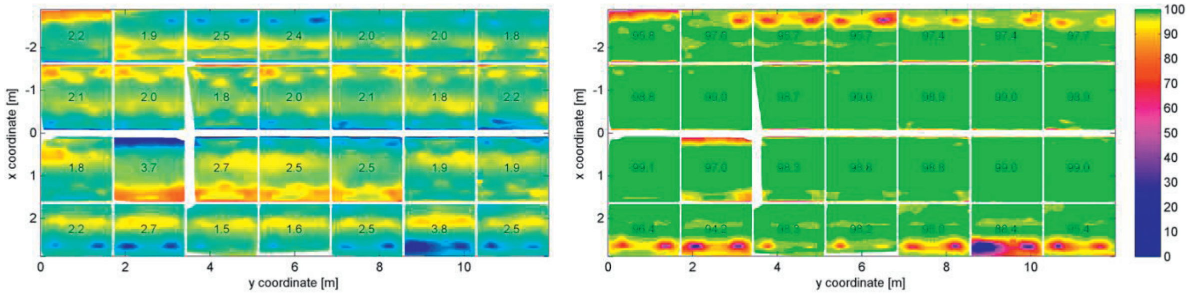


Figure 5. Left: space-resolved slope deviation with panel RMS values in mrad. Right: space-resolved intercept factor with mean values in %.

4.3. Alignment of receivers in collector

In Figure 6 two typical alignment results are given. S6 to N6 refer to the collector modules, D is the drive.

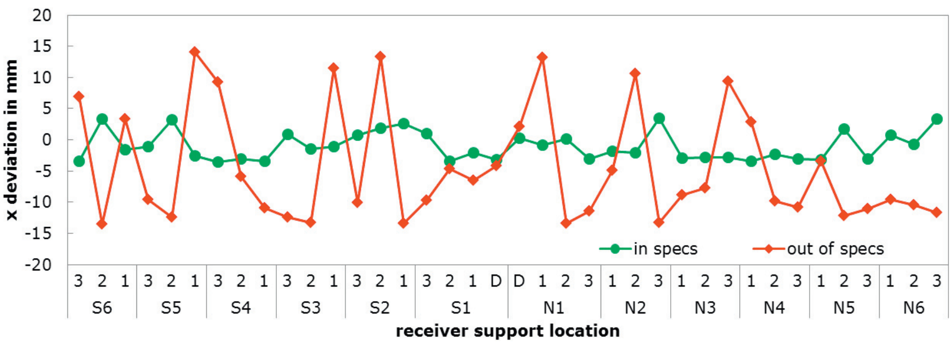


Figure 6. Receiver alignment deviations for a EuroTrough collector before (out of specs) and after improvement (in specs).

The green values corresponding to a good alignment with 2.5 mm RMS give an intercept factor of 98%, the red values with 10.1 mm RMS give 95% intercept (30° sun incidence angle and adherence of other specs in Table 2 for all other deviations assumed). Vertical and transversal receiver alignment are measured in high accuracy with photogrammetry [11,26]. A simpler and faster measurement method using a hook rod is based on the measurement of the distance between receiver and outer mirror rim on both sides of the module. The transversal deviation of the receiver is evaluated by using the measured distances. The measurement accuracy of 2-3 mm depends on the precision of mirror panel assembly and of the eccentricity of the absorbers in the receivers. It is lower than with photogrammetry, but is sufficient to provide satisfactory receiver alignment values for whole collectors.

4.4. Alignment of modules in collector

In the construction phase of solar fields, an adequate method to align all modules of one collector is required. To determine the performance-relevant angle offsets of the modules to the drive, several measurement techniques are in use. When a reference axis is available usually inclinometers are applied. Another method is checking of height differences of the outer mirror rims with a surveyor's optical level, with a (robotic) tachymeter or with a water hose level. As the outer edges are 5.8 m apart, a measurement uncertainty of 1 mm translates into an angular uncertainty of 0.17 mrad. For spot checks on individual collectors or loops, lightweight and mobile water levels are preferred.

4.5. Collector torsion

The torsional behavior of a collector is determined by its torsional stiffness, imbalance of the modules in respect to the rotation axis, friction in bearings and ball joints and possible play. To find out the torsion behavior during operation it is sufficient to measure the torsion angle between drive and collector end in the two opposite horizon collector angles only. Typical torsion measurement values of an imbalanced collector with high friction and a balanced collector with low friction are illustrated in Figure 7. The balanced collector shows horizontal connection lines (green) from the horizontal collector angles from east to west (0° to 180°), while the imbalanced collector has inclined connection lines (red). The torsion due to friction is given in the splitting of the torsion curve for both turning directions.

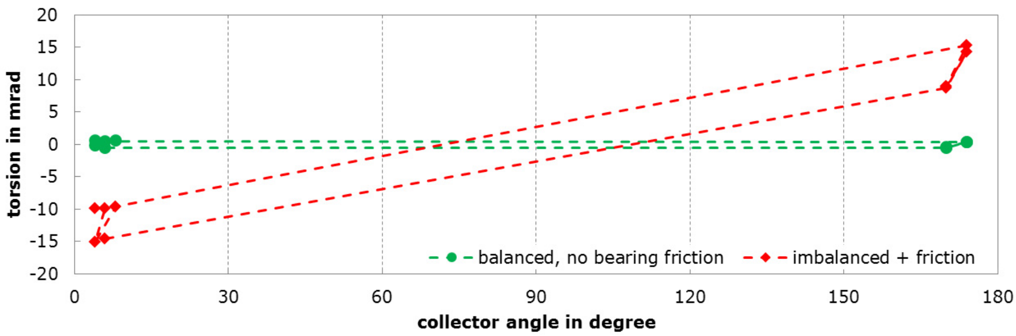


Figure 7. Typical torsion measurement curves. 0° is eastern horizon, 90° zenith and 180° western horizon collector angle.

In the imbalanced collector example, the rotation axis is positioned too low and the upper module parts with mirrors and receivers are heavier than the framework. The torsion between drive and the end of the collector due to imbalance reaches 12 mrad. The torsion due to friction in bearings is about 3 mrad (half of the hysteresis between the two red lines). The green values result in an intercept factor of about 98%, the red values deliver about 80% intercept (30° sun incidence angle and adherence of other specs in Table 2 for all other errors assumed).

5. Intercept factor measurement during operation on sun

During solar field operation the local intercept factor varies along the collector row due to a variety of causes. To check the local intercept factor over an entire collector, the Camera Target Method (CTM) is applied [5,11]. CTM is based on image recognition in photographs of the irradiated target, which is placed in the focal line of an operating parabolic trough perpendicular to the receiver (Figure 8). On the irradiated target, flux densities vary and optical losses behind the absorber tube are made visible. The quantitative measurement results include all effects of collector, module, mirror and receiver geometry as well as alignment, torsion, tracking and sunshape effects on the local intercept factor. In case of collector optimizations (tracking, module and/or absorber tube alignment, balancing, friction reduction, etc.), CTM can be used to visualize the improvements qualitatively and quantitatively. For this application CTM is performed before and after the optimization under similar measurement conditions.

Figure 8. Intercept factor measurement of a parabolic trough collector with Camera-Target-Method with examples of measurement images.

Figure 9 shows an example for improvements due to an alignment and torsion optimization. The curves provide a direct feedback of the benefit of the optimization. The red curve represents an average intercept factor of 89%, the green curve of 97%.

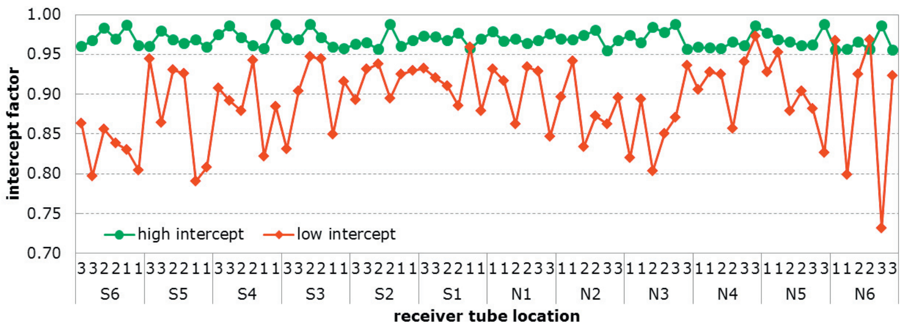


Figure 9. Intercept factor of a trough collector before and after optimization. S6 to N6 refer to the 12 modules of the collector, D is the drive.

6. Conclusion and outlook

A list of specifications for parabolic trough collectors of EuroTrough geometry has been developed by using the experience and expert knowledge acquired during measurements of prototypes and mass produced collectors. Statistical ray-tracing confirms the specifications and helps to quantify reasonable tolerances in the component production and assembly of parabolic trough solar fields. The intercept factor improvement potential of a EuroTrough-type collector has been analyzed according to the presented statistical beam spread. Basically, in case a collector fulfills the suggested specifications, the intercept factor remains high even with some deviations slightly higher than specified. However, single high deviation parameters can dominate the total beam spread quality and spoil the intercept factor. The analyses also show that certain intercept factor losses which are due to systematic deviations can be partially compensated by tracking adjustments. A bundle of optical and mechanical tests is available for solar field assembly to assure the compliance with the presented specifications. They allow the detection of geometrical shortcomings, and countermeasures to improve the product quality and performance can be implemented. The recommended quality assurance approach is suggested to be implemented in solar power plant construction projects, leading to improved energy output and better economic project performance.

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